Inundation maps for the State of California

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Abstract. More than 20 tsunamis of different heights have impacted the State of California in the past two centuries. While some earlier 19th century reports are subject to interpretation, there is little question that offshore seismic sources exist and could trigger tsunamis directly or through coseismically generated submarine landslides or slumps. Given the intense coastal land use and recreational activities along the coast, even a small hazard may pose high risk. California presents nontrivial challenges for assessing tsunami hazards, including a short historic record and the possibility of nearshore events with less than 20 min propagation times to the target coastlines. Here we present a brief history of earlier efforts to assess tsunami hazards in the state, and our methodology for developing the first generation inundation maps. Our results are based on worst case scenario events and suggest inundation heights up to 13 m. These maps are only to be used for emergency preparedness and evacuation planning.

1. Introduction

Up until 1992, the tsunami hazard in California was primarily attributed to teletsunamis, i.e., to tidal waves generated farfield. Pre-1985 hazard predictions had only identified an overall small risk, subject to numerous disclaimers. As a result, most of the tsunami risk reduction in the U.S. concentrated on mitigating the hazard in Hawaii and Alaska. The 1992 Cape Mendocino tsunami led to more comprehensive analyses of historic events in California. McCarthy *et al.* (1993) conclude that risk from locally generated (nearshore) tsunamis is believed to be high along the coast from Crescent City to Cape Mendocino, moderate south of the Cape to north of Monterey, high south of Monterey to Palos Verdes, and moderate south of Palos Verdes to San Diego.

In the period 1992–1999 and immediately following the Cape Mendocino event, eleven large earthquakes around the Pacific Rim generated local tsunamis with run-up heights ranging from 5 to 30 m. Before these events, the last major tsunami of similar magnitude occurred in 1983. These events caused extensive inundation and claimed the lives of at least 4000 people. The post-event surveys produced field data at exactly the time when inundation codes had started breaking the computational barriers of the notoriously difficult run-up calculation. At the same time seismological models started producing accurate deformation contours instead of average elevations across the deformed area. Also, field surveys identified previously unrecognized coastal and seafloor features which greatly increase the inundation potential, as well as unidentified generation mechanisms. For example, before

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the 1994 Mindoro event, strike-slip faults were not believed to be capable of triggering damaging tsunamis, while before the 1998 Papua New Guinea event the hazard from landslide waves remained largely under-appreciated. Even now, the differentiation between slow earthquakes and mass movements (Synolakis *et al.*, 1997, 2001) remains controversial, but it is believed that as many as 30% of recent tsunamis were triggered by coseismic slides and slumps.

The 1992–1999 tsunamis have proven unfortunate fortuitous opportunities to measure actual inundation heights and help further develop and validate inundation models. While pre-1994 inundation computations underestimated the inundation height, newer inundation models have now proven capable of modeling extreme events accurately. The code known as MOST, for example, accurately predicted the 30 m high run-up values and 20 m/sec overland currents measured and inferred during the Hokkaido-Nansei-Oki tsunami of 1993 (Titov, 1997; Titov and Synolakis, 1997, 1998). Inundation models such as MOST permit quantitative evaluation of the inundation from nearfield tsunamis, provided accurate regional tectonic models exist and accurate high resolution bathymetry.

Even using these state-of-the-art inundation prediction tools, California presents unique challenges in assessing tsunami hazards. One, there is an extremely short historic record of tsunamis in the state. Whereas some areas of the Pacific have records dating back 1000 years or more, in California there are none known before the 19th century. About 20 tsunamis have been reported since 1800, but in most cases the information is not sufficient for reasonable inferences of the inundation. Two, most of the geologic work in the state has concentrated on identifying the risks associated with onshore faults and there is scant available information on offshore faults or landslide and slump scars suggestive of past submarine mass failures. Three, earlier estimates of tsunami hazards had relied almost entirely on farfield sources and had used pre-1980s technology. This had created the impression among policy planners and the general public that the tsunami hazard was small. Four, nearshore seismic events may trigger tsunamis arriving within less than 20 min from generation, allowing little time for evacuation. Here we review earlier studies assessing the inundation potential from tsunamis in the state and we describe our methodology for developing the first generation of inundation maps for mitigating tsunami hazards.

As a preamble, we will define the terms run-up and inundation, which are sometimes misused. Wave *run-up* is the rush of water up a structure or a beach; it is also called the uprush. The *maximum run-up* is the vertical height above stillwater that the rush of water reaches as it climbs onshore. The term *inundation height* is a term often used interchangeably with run-up, but it refers to either the maximum flow depth or run-up along a particular transect. Both parameters are rarely determinable in the field, although they both can be computed with MOST. Specific knowledge of the maximum wave run-up on a given beach is essential both in shore protection and in the design of coastal structures. In earlier pre-1990s studies the term *tsunami height* offshore was used interchangeably with run-up height. Tsunami height references are generally not useful in inundation prediction as the tsunami height varies substantially with depth, particularly in the extreme nearshore region. *Inundation* refers to the horizontal distance the wave penetrates inland. Depending on land use, either run-up or inundation are relevant, and most often both. In addition, the wave-front velocity as the wave strikes the shoreline is an important design parameter for coastal structures. An *inundation computation* includes predictions of run-up heights, inundation distances, and inundation currents. *Threshold* models are fairly common and compute the tsunami height at the shoreline or worse at some depth contour offshore and then project it inland to infer inundation; they are erroneously referred to as inundation models. An inundation map includes a line corresponding to the maximum penetration of the tsunami wave triggered by the event under study.

2. Existing Analyses of Tsunami Hazards in California

The most comprehensive calculation of tsunami hazards for California is the work of Houston and Garcia (1974) and of Houston (1980), both of which focused on the hazard in Southern California from farfield events. McCulloch (1985) also focused on the hazards in the Los Angeles region primarily from farfield events, but also considered several local events. Satake and Sommerville (1992) analyzed the Lompoc 1927 earthquake and the associated local hazards. In a comprehensive review, McCarthy *et al.* (1993) analyzed the historic records of tsunamis in California and predicted qualitatively the hazard over the entire state. Table 3 lists the possible tsunamigenic sources they identified. Synolakis *et al.* (1997) reviewed pre-1997 studies and observed that the earlier run-up estimates did not include inundation calculations. When performed with the new generation of inundation models, run-up estimates were up to 100% higher than what the earlier calculations suggested. Borrero *et al.* (1999, 2001) studied nearshore tectonic, landslide, and slump sources in East Santa Barbara channel and produced run-up estimates ranging from 2 m to 13 m.

2.1 The hazard from farfield events

Houston and Garcia (1974) used a combination finite-difference solution (FD) and analytic solution of the linearized shallow-water wave equations (LSW) to calculate tsunami propagation, except in the Santa Monica and San Diego bays where they used a finite-element solution (FE) to resolve possible local resonance effects. They argued that the only reliable data for defining source characteristics at that time were from the 1964 Alaskan and the 1960 Chilean earthquakes. Based on these data, they approximated the initial ground deformation by a hypothetical uplift mass of ellipsoidal shape, about 600 miles long with an aspect ratio of 1:5 and maximum vertical uplift of 8–10 m. They then divided the Aleutian trench into segments and calculated the wave evolution from each segment, and repeated the procedure for tsunamis from the Peru-Chile trench. Some representative results for the

Table 1: Houston and Garcia (1974) tsunami height predictions "close" to shore.

Location	R_{100} (ft)	R_{500} (ft)
La Jolla	6.1	12.7
San Onofre	5.7	11.1
Newport Beach	6.1	10.8
Long Beach	7.0	9.7
Dockweiler Beach	9.6	15.3
Topanga	10.4	16.6
Ventura	10.5	21.7

100-year (R_{100}) and 500-year (R_{500}) tsunami run-up heights are summarized in Table 1.

For their time, Houston and Garcia's methodology and their calculations were groundbreaking in their combined use of analytical and numerical methods. They first solved the linear for spherical long-wave equations and they propagated the tsunami from the source to the edge of the continental shelf, by using a finite difference model. At the continental shelf, they derived an analytic expression to match the outer and inner wave amplitudes, and then they used that expression to derive a simple amplification factor for a sinusoidal tsunami. Even though they did not match the slope of the water surfaces in the inner and outer continental shelf regions, their results compared well with measurements from tidal gage records, whenever suitable tidal gage records were available and did not need additional signal processing to filter harbor resonance effects. These comparisons are presented in Table 2.

The excellent accuracy of these predictions for the 1964 Alaskan event encouraged the extrapolation of their results for nearfield events, despite Houston and Garcia's (1974) disclaimers, without considering the limitations of extrapolations. One, the methodology used for farfield events may not be applicable for nearshore tsunami sources. Two, in the middle 1980s it became apparent that superposition of sinusoids is not as straightforward as previously assumed; the reason is that during the reflection process—not accounted in Houston and Garcia's calculation—there is a phase lag introduced which is frequency dependent (Synolakis, 1987; Liu *et al.*, 1991). Three, comparisons of numerical model predictions with the field data from the field surveys of the 1992–1999 tsunamis suggested that even small-scale nearshore features can influence inundation to first order, casting doubt on predictions from coarse grid computations, because they may miss extreme run-up. Four, no landslide or slump sources were considered as possible sources and used as initial conditions.

Houston (1980) performed another comprehensive study for tsunami predictions in California in a series of two reports, Houston and Garcia (1978), and Houston (1980). By this time, numerical solutions of the shallow water wave equations were possible but very difficult. They solved using finite dif-

Table 2: Houston and Garcia (1974) predictions for the 1964 Alaskan tsunami.

Location	Predicted (ft)	Observed (ft)
Alamitos Bay	2.2	1.8
Santa Monica	2.8	2.6
Avila Beach	3.7	4.4
Crescent City	7.3	8.0

ference algorithms the nonlinear form of the shallow-water wave equations (NSW), including frictional terms. Even though these newer computations were an improvement over the 1974 study, it is important to consider the assumptions of these 1978 and 1980 predictions:

1. Only farfield events from Alaska and South America were considered.
2. The Pacific ocean was modeled as a 500 m constant depth basin with a 2 mile square grid. In the nearshore region, the bathymetry was also modeled with a 2 mile square grid, and the transition between the offshore and nearshore grids was at least one and one half wavelength of a 30 min wave.
3. The computational boundary was a vertical wall at the shoreline, i.e., they used a threshold model and thus made no inundation computations.

Houston (1980) noted that the run-up elevations, i.e., the elevation of the maximum inland penetration of the tsunami, may not equal shoreline elevations at locations where dunes prevent flooding, or if the land is flat, where inland flooding may be extensive. Houston (1980) used the best available methodology of the time, i.e., threshold modeling which propagates the wave close to the shoreline, where a vertical wall is placed to facilitate the numerical computations. However, the land use in the state is often most intensive in flat beach areas such as in Venice, Malibu, or Santa Barbara, or where there are dunes, such as in San Francisco south of the bay entrance. Although the degree of underprediction varies with the local topography, it is often a factor of two or even higher. Hence Houston's (1980) results are not helpful in assessing the hazard from nearshore events over large portions of population centers in the state.

Nonetheless, even under the fairly restrictive assumptions and the 1970's technology used for above predictions, the Houston and Garcia predictions even at face value are a substantial cause of concern, a fact not fully recognized until the post-1992 tsunami field surveys.

2.2 Hazards from nearshore events

As noted earlier all existing studies had focused on farfield events. Houston (1980) noted that the frequency of occurrence of locally generated tsunamis in southern California is not known and predictions of locally generated tsunami elevations were beyond the scope of his reports. McCulloch's (1985) study was a seminal work on tsunami hazard potential in Southern California. McCulloch relied on Houston's results for farfield tsunamis and then used seismological data to make predictions for nearshore events. Since he did not use any hydrodynamic model, he relied on several empirical formulae developed in Japan. These formulae had been extensively used before 1992; since then the availability of high quality run-up data from the 1992–1999 event for many areas around the Pacific have shown that these formulas are only applicable in Japan and that they substantially underpredict the run-up elsewhere.

McCulloch (1985) tried to explain the fairly moderate predictions of Houston by arguing that in "California, the major tsunamis generated in the Pacific-Eurasian plate boundary that have repeatedly decimated the Japanese coast are reduced to small but detectable waves after crossing the Pacific." Referring to local tsunamis, he wrote that four had been observed along the southern California coast during the period of record from 1812 to 1975, for three of which events the wave heights were not indicated. He continued by arguing that in Southern California the displacement between the North American and Pacific Plates is accommodated in part by movements along strike-slip faults, some of which are in the offshore borderland. He found some suggestive evidence of episodes of vertical displacement capable of tsunami generation associated with the offshore extension in the Palos Verdes Hills reverse fault to the southwest in an area otherwise dominated by strike-slip displacement. McCulloch (1985) did not provide any run-up estimates from nearshore events, but his work implies that the hazard is low.

McCulloch's assessments for nearshore tsunamis were scrutinized by Synolakis *et al.* (1997) who argued against their indiscriminate use on the following grounds.

1. Before the 1994 Mindoro event (Imamura *et al.*, 1995), where a strike-slip fault generated a moderate tsunami which caused spotty but extensive inundation, the hazard from nearshore strike-slip faults was not recognized.

2. McCulloch relied on the relations between tsunami size, earthquake magnitude, and hypocentral depth established for Japanese earthquakes.

McCulloch used the Japanese data to argue that a local seafloor earthquake having a magnitude of 7.5 and a hypocentral depth of 4 km to 14 km could produce a tsunami accompanied by a run-up height of 4 m to 6 m. In 1985, a 6 m tsunami may have appeared a marginal hazard, even though the tsunami height in the 1964 Alaskan tsunami in Crescent City was about 6.2 m, while the run-up height was 3.8 m. The 1992–1999 post-event field surveys have shown that even a 4 m tsunami can cause extensive damage and flooding in flat coastlines, such as those in Santa Monica bay or in Orange and San Diego counties.

Table 3: Summary of historic reported tsunamis, known local faults, and offshore canyons (modified from McCarthy *et al.*)

Source Zone	Major Offshore Faults	Major Submarine Canyons	Maximum Historical Earthquake	Historical Tsunami
Crescent City to Cape Mendocino	Little Salmon Fault (T) Mad River Fault Zone (T) Mendocino Fault (S) Cascadia Subduction Zone (T)	Trinity, Eel, Mendocino, Mattole	$M_s = 7.4$ (1923) $M = 7.2$ (1923)	1.1 m (1992)
Cape Mendocino to San Francisco	San Andreas Fault (S) Point Reyes Fault (T)	Spanish, Delgada, Vizcaino, Noyo Navarro, Arena, Bodega	$M = 7.7$ (1906)	0.1 m (1906)
San Francisco to Monterey	San Gregorio Fault (S)	Pioneer, Ascension, Monterey	$M = 7.1$ (1989)	0.3 m (1989)
Monterey to Point Arguello	Hosgri Fault Zone (RS) Santa Lucia Bank Fault (RS?)	Sur, Lucia	$M_s = 7.3$ (1927)	3–4 m (1812)
Point Arguello to Los Angeles (Santa Barbara Channel and Santa Monica Bay)	Santa Barbara Channel faults (T) Anacapa-Dume Fault Zone (RS) Santa Monica Fault (T)	Arguello, Hueneme, Mugu, Dume, Santa Monica, Redondo	$M_i = 7$–7.5 (1812)	3–4 m (1812)
Los Angeles to San Diego (Inner Borderland)	San Clemente (R) Catalina—San Diego Trough (S, RS?) Paolos Verdes (RS), Coronado Bank (NS) Newport-Inglewood, Rose Canyon (S)	San Gabriel, Newport, Carlsbad, La Jolla, Coronado	$M = 6.25$ (1933)	Uncertain (1862, 1933)
Northern Channel Islands to San Nicolas Island (Northern Outer Borderland)	East Santa Cruz Basin Fault Zone (S) Ferrelo Fault Zone (S) San Nicolas Island Escarpment	Santa Cruz	$M_L = 5.1$ (1969)	?
San Nicolas Island to Mexican Border (Southern Outer Borderland)	East Santa Cruz Basin Fault Zone (S) Ferrelo Fault Zone (S)	unnamed	$M_L = 5.3$ (1948)	

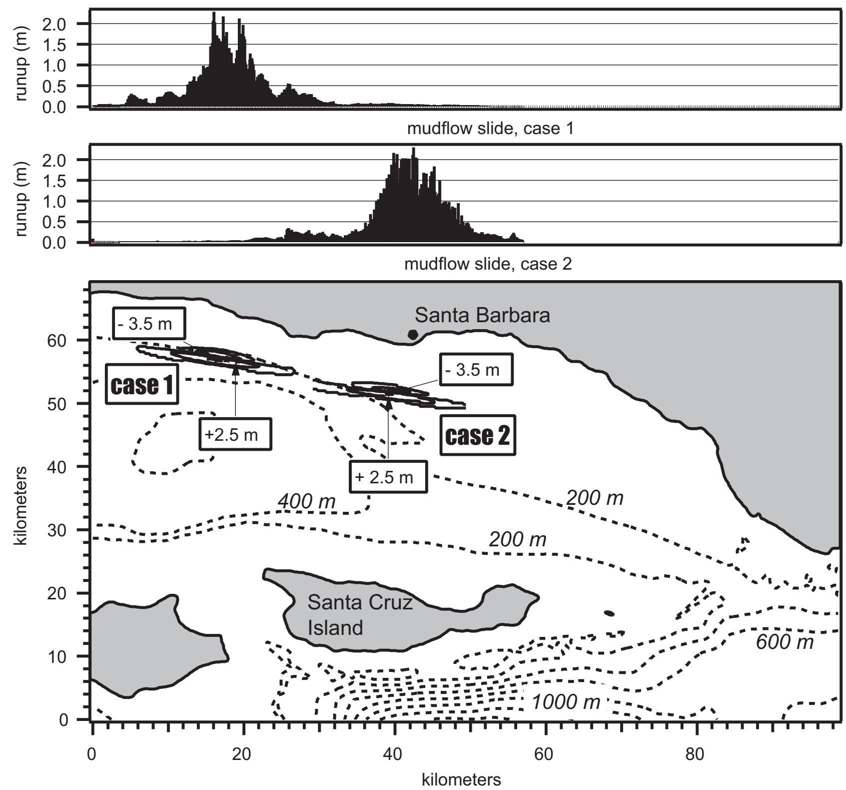
Explanation: Fault Character: T = Thrust of Reverse, RS = Reverse-Oblique, S = Strike-Slip, NS = Normal-Oblique
Magnitude: M = Moment Magnitude (M_w), M_s = Surface Wave Magnitude, M_L = Local (Richter) magnitude, M_i = Seismic Intensity Magnitude, ? = Magnitude not given or unknown

Perhaps the most serious limitation of McCulloch's assessments is his conclusion that landslide generated waves would be small. He based his analysis on the best empirical formulae available at the time, and a hypothetical slide of 5 km length, 50 m thickness sliding over 100 m downslope was calculated to produce a 0.014 m initial wave height tsunami. Using more recent tools as in Borrero *et al.* (2001), the initial wave height for such a slide can be as high as 15 m, depending on the slope.

McCulloch (1985) also presented an interesting analysis of the cost associated with tsunami events. He compared the cost of damage in California from the 1964 Alaskan tsunami of $32 M in 1983 dollars to the combined cost of all 26 historic earthquakes in the period of 1812 to 1975. He concluded that although the cost of a tsunami in California was 0.2% of the combined cost of the 26 events, the bulk of the cost was incurred in Crescent City, where 11 of the 13 reported state tsunami deaths occurred.

McCarthy *et al.* (1993) performed a systematic analysis of all historic and possible tsunami hazards in California and they qualitatively calculated the tsunami hazard in California as *high* along the coast from Crescent City to Cape Mendocino, *moderate* south of the Cape to north of Monterey, *high* south of Monterey to Palos Verdes, and *moderate* south of Palos Verdes to San Diego. Synolakis *et al.* (1997) revisited the McCarthy *et al.* estimates and identified the need for modeling from nearshore events. As an example, they considered a hypothetical fault rupture along the San Clemente fault. They found that results using the older pre-1980 methodology were as much as 50% lower than results using current inundation models.

Borrero *et al.* (2001) studied tsunamis in East Santa Barbara Channel using the state-of-the-art inundation code used by NOAA/PMEL and known as MOST. They considered tsunamis generated from coseismic displacements from thrust faults underlying the Santa Barbara Channel. They also considered tsunamis generated by slope failures along the walls of the Santa Barbara Channel. Their results include predictions from the Gaviota mud flow (Edwards *et al.*, 1993) and from the recently mapped Goleta slide (Greene *et al.*, 2000). They used a variety of publicly available maps and sources to develop a 250 m $\approx$ 9 arcsec computational grid including Scripps Institution of Oceanography 3 arcsec grid of nearshore bathymetry. Examples of their work and of run-up distributions along the coast of Santa Barbara County are shown in Fig. 1. Interestingly, their results are consistent with earlier reports of 9 m run-up for the 1812 tsunami (McCulloch, 1985) revised by reference to other earlier unpublished reports to 3–4 m. Borrero *et al.* (2001) found that purely tectonic sources could generate tsunamis with $\approx$2 m run-up, while a combination of tectonic sources and submarine mass movements could generate extreme run-up of $\approx$20 m in one location. Overall, they observed narrow run-up peaks and warned that "A wave of this size anywhere along the populated shores of southern California would be devastating, and further mapping work is urgently needed to quantify this possibility."



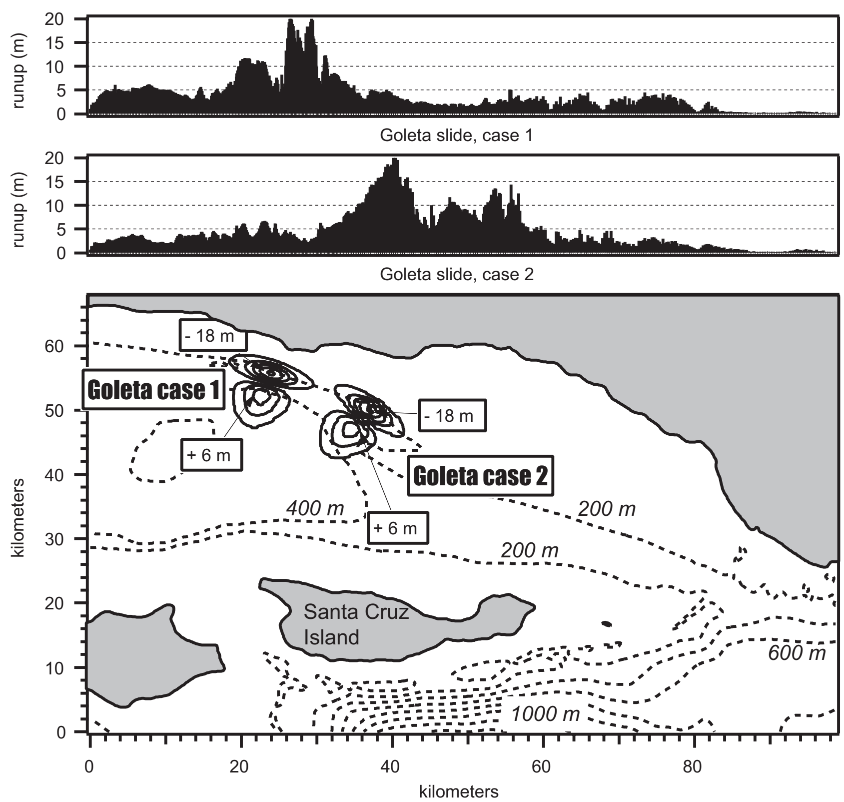


Figure 1: An example of model results and run-up calculations based on two different landslide tsunami scenarios. The upper panel is based on a small thin landslide. The lower panel is based on a much larger landslide scar recently identified off of Goleta by Greene and Maher (2000).

3. Developing Inundation Maps for the State of California

As early as 1992, the generation of the small tsunami from the Cape Mendocino earthquake was a wake up call that led to the immediate development of inundation maps for Humboldt Bay, using the best available methodology of the time. Maps with inundation projections of 10(?) m were produced using one-dimensional models and no run-up computations. Tsunamis generated nearshore in Nicaragua (1992), Flores, Indonesia (1992), Okushiri, Japan (1992), Mindoro, Philippines (1993), East Java, Indonesia (1994), Shitokan, Russia (1994), Manzanillo, Mexico (1995), Chimbote, Peru (1996) and Irian Jaya, Indonesia (1996) identified the risk from hazards from nearfield events. Clearly, the existing assessments of tsunami hazards in California needed further review.

In 1996, the Tsunami Hazard Mitigation Federal/State Working Group, chaired by PMEL Director Eddie Bernard, prepared a report to the U.S. Congress recommending the preparation of inundation maps for the five states, Alaska, California, Hawaii, Oregon, and Washington. This report is available at http://www.pmel.noaa.gov/tsunami-hazard. The National Tsunami Hazard Mitigation Program (NTHMP) is discussed by Eisner (2001) in this volume. The report recommended the preparation of inundation maps for emergency preparedness and evacuation planning. The report was the springboard for the National Tsunami Hazard Mitigation program which provided resources in all five states for mitigating tsunami hazards.

As early as 1997, California's Coastal Region Administrator of the Governor's Office of Emergency Services (OES), through a series of workshops and publications, informed local governments and emergency agencies of the plans to address tsunami hazards and presented the NTHMP. OES solicited input as to the levels of hazards to be represented on the maps, as the short length of the historic record did not permit a comprehensive probabilistic hazard assessment. As early as 1997, it was decided that the maps would include worst case scenarios to be identified further in the mapping process. In 1998, as funding became available for the state, OES contracted to the Tsunami Research Program of the University of Southern California the development of the first generation of inundation maps for the state.

The State of California has the most densely populated coastlines among all five states in the NTHMP. The state had to utilize the same limited resources as the other four but assess offshore tsunami hazards over a much longer coastline. A comprehensive tsunami hazard evaluation involves both the probabilistic hazard assessment of different farfield and nearfield, onshore and offshore sources, and the hydrodynamic computation of the tsunami evolution from the source to the target coastline. Given the level of funding, this was not feasible, and this presented a major challenge for the state.

Given the quantitative agreement between model results and measurements for the 1964 tsunami of the work of Houston and Garcia (1974), it was decided to focus on nearshore tsunami hazards, which had not been modeled before 1999. As discussed, the Houston and Garcia offshore tsunami height estimates are not accurate over flat coastlines, yet nonetheless newer predictions might be larger by a factor of two. If inundation predictions from nearshore events proved smaller than twice the farfield tsunami results of Houston and Garcia, then farfield sources would have to be considered as well. Early results suggested that for the areas studied, nearshore sources produced higher inundation heights that were twice the 100-year values of Houston and Garcia, hence only nearshore sources were considered.

The state was also faced with the decision of choosing its mapping priorities. By considering the geographic distribution of population centers, the state opted to perform modeling of the Santa Barbara and San Francisco coastlines in year one, of Los Angeles and San Diego in year two, and of Monterey Bay in year three. Recommendations for the next target coastlines are pending but include San Luis Obispo and Orange Counties, with the objective to cover the entire state as funding permits. The next decision was the resolution of the numerical grids to be used in developing the maps. The technology existed for high resolution maps with grids of sizes as small as 5 m square, but this would result in a relatively small spatial coverage with large computational grids and lengthy computations. It was opted to produce maps at 125 m resolution, based on Titov and Synolakis (1997), who had argued that dense grids may improve numerical accuracy but do not improve the realism if the available bathymetric/topographic sets are not of similar resolution. In the State of California, the best available sets varied in resolution between 50 m and 150 m. Also, given the uncertainties in the source mechanism, results with higher resolution would be misleading.

An interesting issue that came up as the mapping progressed was whether to provide emergency planners with inundation results at different levels of risk. For example, one suggestion was to include low- and high-risk lines on the inundation maps. Another suggestion was to provide separate lines for nearfield and farfield events. On discussing these issues with emergency preparedness professionals across the state, it was felt that a single line representing a worst case scenario was preferable, for it simplified the preparedness response and it better informed the general public. Further, without a probabilistic hazard assessment it was difficult to rank the relative risk from different scenarios. Lines identifying risk zones for nearfield and farfield events could also prove confusing for the public. For example, would another Cape Mendocino tsunami be nearfield or farfield in Central California? It was therefore decided to consider for every locale in the region under consideration, the worst case nearshore event that was plausible based on the available historic earthquake and tsunami information.

The inundation mapping effort first identified offshore faults and offshore landslide and slump hazards. Difficulties encountered included the lack of detailed high-resolution marine surveys over all target coastlines. With the exception of marine surveys undertaken by the USGS off Santa Monica Bay and of the Monterey Bay Aquarium Marine Institute (MBARI) off Santa Barbara and Monterey Bay, high resolution surveys are not available for other parts of the state, if indeed they do exist at all. Hence, and given that onshore earthquakes can trigger submarine landslides, in regions where marine geology data did not exist, submarine slopes with soft sediment were considered as possible sources. Offshore faults and slide-prone areas were then used to develop initial tsunami waves as discussed in Borrero *et al.* (2001), and then the inundation model MOST was used to obtain inundation heights and penetration distances along the target coastline.

The inundation predictions for any given event are highly bathymetry and topography dependent and vary substantially along the coast, as shown in the example in Fig. 1 for the Santa Barbara coastline. Since the location of the source is seldom accurately known, the source was moved around within the range of uncertainty. Along California's flat coastlines, this relocation of the tsunami sources resulted in relocation of the maximum along the coast. When asked, emergency planners preferred to have a single value for each region identifying the maximum elevation that tsunami waves from the different local offshore sources would attain. This practice would simplify the communication of the risk to the public and it would provide information that was easy to remember and implement in regional emergency preparedness. For example, a region could plan for tsunami evacuation areas above a certain minimum elevation across its jurisdiction. Hence, in the development of the maps, sources were relocated along the coast and the highest inundation value among different runs identified. Interestingly, in the areas studied there were no areas that consistently experienced higher run-up than adjacent locales. We found that most low lying coastal areas could experience the high run-up, if the source was relocated in an appropriate direction, always within the limit of uncertainty of defining the source. Example maps from four different areas are shown in Fig. 2. Thus the maps do not represent the inundation from any particular event or characteristic earthquake, but the best estimate of the modelers for the largest inundation height within a given region.

The inundation predictions were checked with field surveys in all areas mapped. During each survey, several transects were obtained to check the topographic data used in the computations. The variance of the beach slopes with respect to their numerical description was within the limits of seasonal variation. Also, the surveyors looked for unusual land features that were not present in the digital data sets and made on-site adjustments of the inundation lines based on the team's experience from post-event field surveys, usually reducing the predicted run-up heights.

Once draft versions of the maps became available, OES presented them in regional meetings with emergency preparedness officers and other interested parties such as the State Lands, Seismic Safety, and Coastal Commissions. Further input was solicited, and an emergency response manual with guidelines for mitigation was prepared. OES is continuing to organize meetings between the modelers and the emergency management community whenever implementation questions arise. OES also produced a video for school use and distributed numerous copies of other commercial video programs describing tsunami hazards. The development of the state's inundation maps was featured in two Discovery Channel documentaries and in numerous national and local news stories.

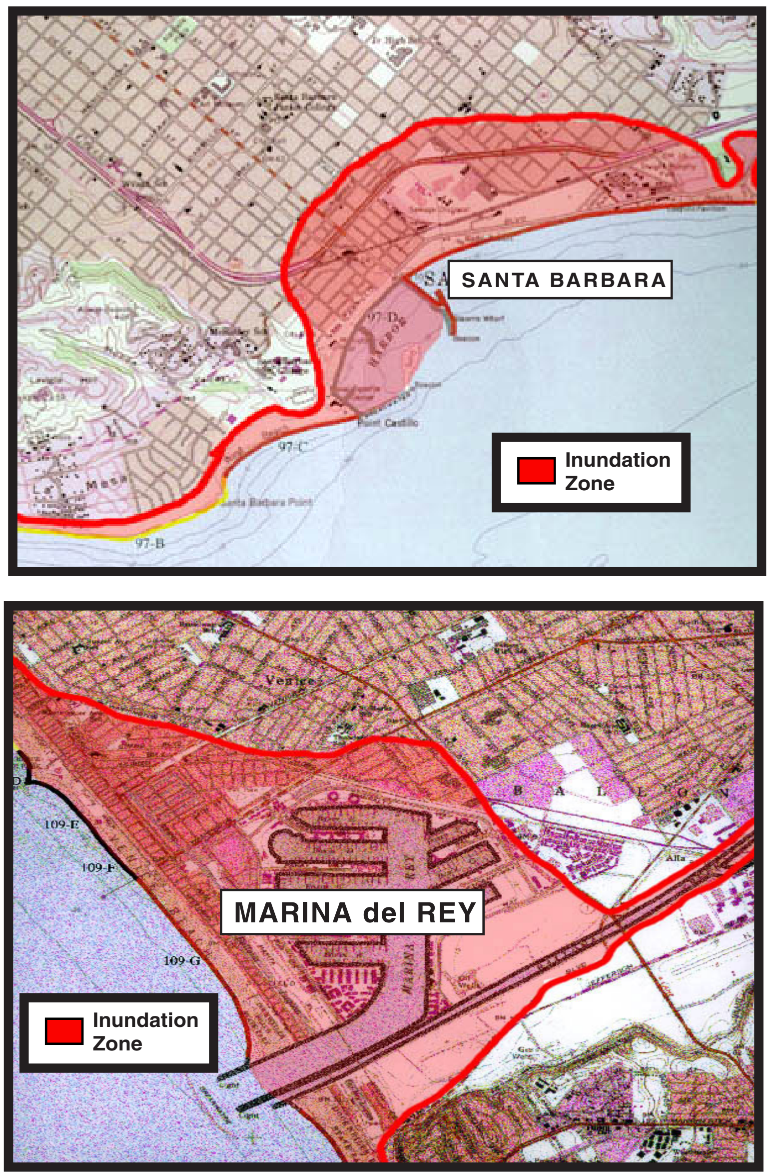


Figure 2a: Examples from California's inundation maps. Upper panel is the region around Santa Barbara, lower panel the region around Marina Del Rey in Los Angeles.

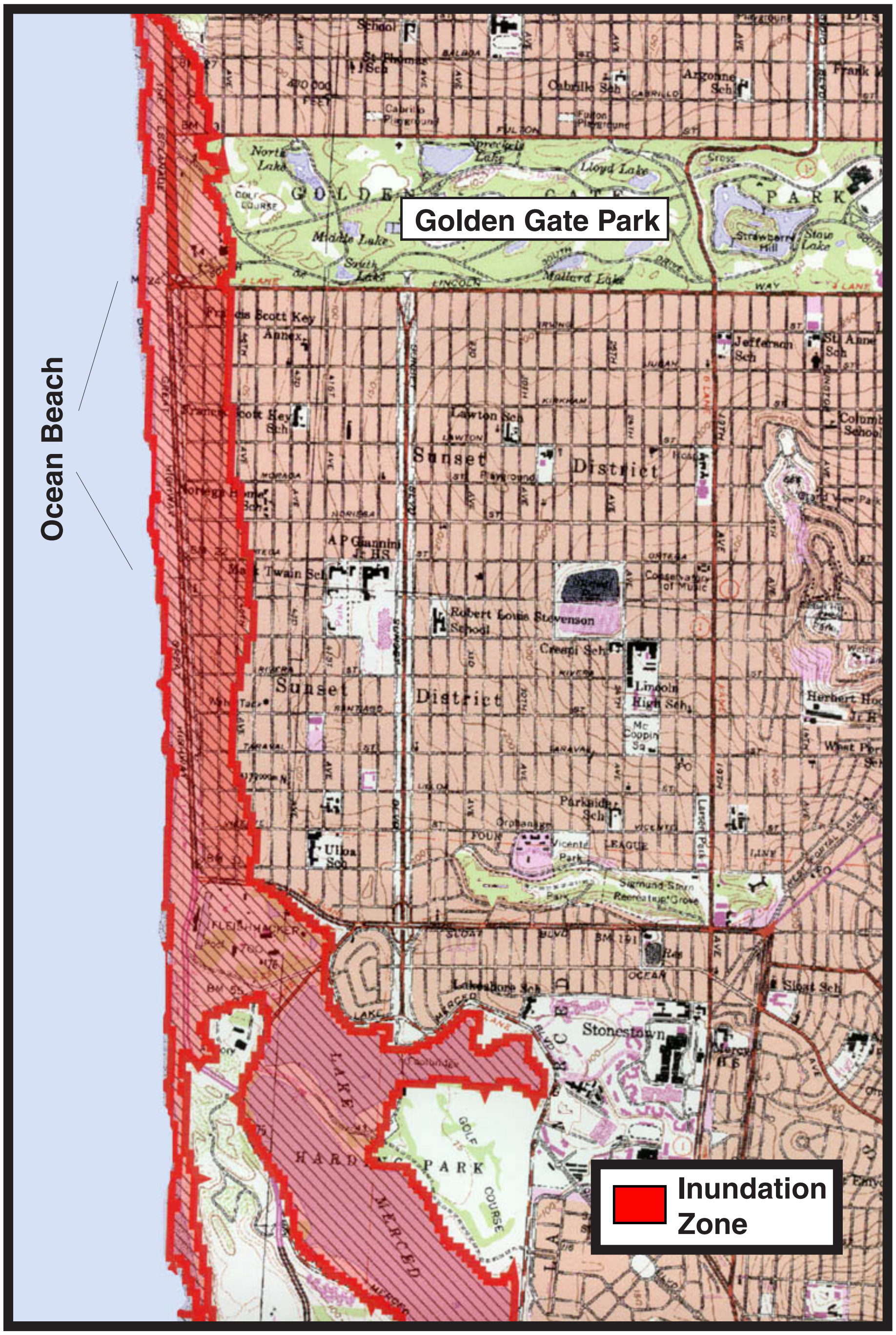


Figure 2b: Example from California's inundation maps: the coast from the Golden Gate south to Lake Merced.

4. Summary

The State of California now has its first tsunami inundation maps covering a significant portion of the state. The maps were developed based on offshore tsunami sources, including both tectonic motions and underwater mass movements. The mapped inundation line is based on run-up computations developed by relocating worst case offshore sources that trigger tsunamis within the range of uncertainty. The maps are for emergency preparedness and evacuation planning only.

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